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Bioenergy from landfill gas (LFG) in Taiwan

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Abstract

Greenhouse gases (GHGs) emissions are becoming significant energy and environmental issues relating to municipal solid waste (MSW) deposited in landfills in Taiwan. The nation, although not a Party to the Montreal Protocol and Kyoto Protocol, has diligently striven to mitigate and phase out them. The landfill gas (LFG), which is now considered as a renewable energy with emphasis on electricity generation, has been recognized as one of the main GHGs emissions associated with its composition mostly consisting of methane (CH_4) and carbon dioxide (CO_2). The objective of this paper is to present an updated overview of LFG-to-electricity in Taiwan. The description is thus centered on biogas sources and their energy utilizations, and then aimed at MSW generation and management. Using the International Panel on Climate Change (IPCC) recommended methodology, anthropogenic methane emissions from MSW landfills in Taiwan during 1992–2003 were estimated to be around 360 thousand metric tons annually during 1992–1999, then decreased to approximately 103 thousand metric tons in 2003 due to the MSW recycling and incineration policies during this period. The promotion measures relating to LFG-to-electricity are also summarized in the paper. Finally, we overview four LFG-to-electricity facilities currently commercialized in Taiwan, and briefly evaluate their economic and environmental benefits. It is shown that total LFG-to-electricity is around 1.6×10^8 kW − h/yr based on the LFG generation rate of 1.0×10^8 m^3/yr, heating value of 5500 kcal/m^3, and energy efficiency of 25%.

Keywords: Landfill gas; Emission estimation; Promotion measure; Energy policy; Bioenergy

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1. Introduction

The increasing demand for energy has tailed on economic growth and raised living standards in Taiwan. It, however, is a high energy-importing country. National dependence on imported energy rose from 87.25% in 1983, 95.68% in 1993 to 97.65% in 2003 [1]. On a parallel with the dependence data, the domestic energy consumption also increased from 31.6 million kiloliters of oil equivalent (KLOE) in 1983, 61.6 million KLOE in 1993 to 103.4 million KLOE in 2003. The growth rate for domestic energy consumption averaged at about 6.1% per year. In this regard, renewable energy has been considered as an attractive green energy based on the energy policy for diversifying energy supply and enhancing environmental protection in Taiwan. On the other hand, Taiwan is a subtropical nation with a total area of ca. 36,000 km^2 and a population of over 22 millions. With the Taiwan's economic development called 'economic miracle' in the 1970s and 1980s, some environmental issues such as municipal solid waste (MSW) management have become public nuisance. Thereafter, Taiwan Environmental Protection Administrations (EPA), the primary central government-level agency responsible for environmental protection, began to promulgate stringent regulations to establish an integrated MSW management system at the beginning of 1990s [2].

The managed (sanitary) and unmanaged (open dumping) landfills were the primary MSW treatment methods adopted during the 1980s and 1990s in Taiwan. The landfill gas (LFG) is inevitably generated as a result of the biological (anaerobic) decomposition of MSW deposited in landfills. It is well known that LFG is a flammable and odorous gaseous mixture consisting mostly of methane (CH_4) and carbon dioxide (CO_2) together with a few of hydrogen sulfide (H_2S), nitrogen (N_2) and volatile organic compounds (VOCs) [3]. In the past, the odor problem and air quality deterioration derived from LFG arose the public concern, resulting in the development of LFG clean-up controlled by combustion and chemical cleaning. However, with the advent of global warming concerns during the mid 1990s, the interest in LFG utilization for electricity generation and other

energy conversions became widely acceptable because the LFG is one of the major emission sources of anthropogenic greenhouse gases (GHGs) such as methane, accounting for 60–70% of total methane emissions in Taiwan [4].

In response to the Kyoto Protocol adopted in Dec. 1997, Taiwan convened the National Energy Conference in May 1998. One of the most important conclusions was to increase the share of renewable energy in Taiwan's total energy supply, up to 3% in 2020 [5]. For this reason, energy strategies and policies for promoting renewable energy must be active in providing some environmental, financial and economic incentives. With respect to energy policy for economic development and sustainable development, the Executive Yuan has revised and approved 'The Energy Policy of the Taiwan Area', implemented by the Bureau of Energy under the Ministry of Economics Affairs [5], primary agency responsible for industrial development and energy policy in the central government level. The relevant points of energy policy include the production of green energy, mitigation of GHGs, and promotion and demonstration of renewable energy. For example, target share from LFG-to-electricity in term of installation capacity is 30 MW by 2004, 35 MW by 2010, and 43 MWby 2020 [6]. The objectives of this paper will present an updated review and innovative information on energy utilization from LFG in Taiwan. These approaches and progresses will be expected to offer cost-effective measures for pursuing sustainable development referring to United Nations Framework Convention on Climate Change (UNFCCC) and other global environmental issues. The main subjects covered in this paper are as follows:

- Status of biogas sources and their energy utilizations.
- Overview of MSW generation and management.
- Estimation of methane generation from landfills.
- Governmental strategy for promoting LFG utilization.
- Status of electricity generation from LFG.
- Benefits of GHGs emissions reduction from LFG-to-electricity.

2. Status of biogas sources and their energy utilizations

Biogas is a flammable mixture consisting mainly of CH_4 and CO_2 with minor amounts of moisture, H_2S and volatile organic compounds VOCs [3]. Basically, biogas is generated from the anaerobic decomposition of biomass wastes and/or residues such as MSW, biosludge and organic wastewater. In Taiwan, the biomass resources that have been used to produce biogas can be roughly divided into four sources, which are summarized in Tables 1 and 2, and shown in Fig. 1. These biogas sources are further addressed as follows:

2.1. Municipal solid waste (MSW) landfill

LFG mostly results from the anaerobic decomposition of biodegradable fraction (e.g. kitchen garbage) in the MSW that is disposed of to landfills. Notably, the biogas production rate typically starts after the MSW deposition and gradually increases for a lasting period that depends on the MSW composition, disposal practice, local weather, and landfill site characteristics. Because of improving air quality and mitigating GHGs emissions, the energy utilization of LFG for generating electricity and heat recovery is

Table 1
The categories and energy utilization status of biogas in Taiwan

Waste/wastewater category	Sources	Current energy utilization	Examples
Municipal solid waste	Sanitary landfill site	Electricity generation	Purchased by power plant
Sewage wastewater	Municipal wastewater treatment plant	Boiler fuel, electricity generation	Used for maintaining the operation of biosludge digestion tank, the heated swimming pool
Industrial wastewater	Petrochemical/ chemical/ food processing plant	Boiler fuel, electricity generation	Process steam
Agricultural wastewater	Hog farmer	Heater/combustor fuel, electricity generation	Used for the stove, water heater, piglet warming, etc.

Table 2
Status of biogas for electricity generation in Taiwan

Source	Installation capacity (kW)	Percent (%)	Comments
MSW landfill	24,514	95.7	There are four MSW landfill sites that install LFG-to-electricity system. A few of MSW landll sites are being planned to install the bioenergy system.
Hog farmer	~790	3.1	There are approximately 31 hog farmers that install biogas-to-electricity facility in the waste water treatment system.
Food-processing plant	210	0.8	There are two food-processing plants that install biogas-to-electricity facility in the wastewater treatment system.
Chemical plant	110	0.4	There is only one tape-manufacturing plant that installs biogas-to-electricity facility in the wastewater treatment system.
Sewage treatment plant	—	—	A few of sewage treatment plants are being planned to install biogas-to-electricity facility.
Sum	~25,624	100	

Source: [6]; Some data were updated by the available websites (http://www.moea.gov.tw; http://ww.taipei.gov.tw) and the researcher at Energy and Resources Lab of Industrial Technology Development Institute (ITRI).

a promising option in recent years [7]. In Taiwan, although most of biogases from MSW landfills were directly released to the atmosphere, there are four LFG-to-electricity facilities that total to approximately 24,514 kW by the installation capacity as listed in Table 2 and shown in Fig. 1. From the data in Table 2, it is obvious that the biogas energy utilization for electricity generation is mostly from LFG sources in Taiwan.

2.2. Sewage treatment plant

During the past two decades, developments in municipal wastewater treatment aim at reducing or eliminating the discharge of organic pollutants into the receiving body and

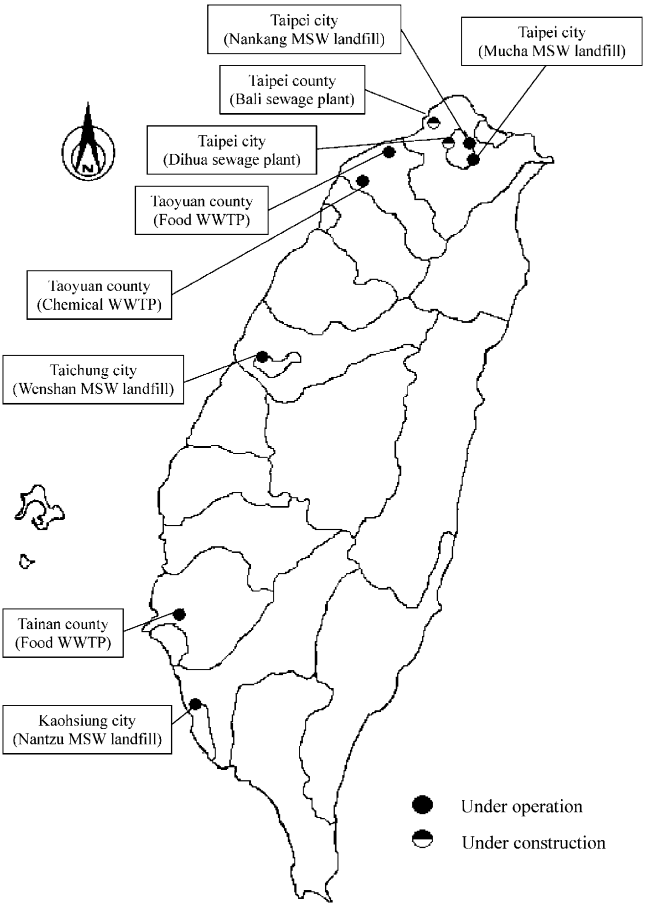

Fig. 1. The location distribution of large biogas-to-electricity plants in Taiwan.

enhancing the effective treatment of sewage sludge produced in the secondary wastewater treatment process [8]. With respect to the sustainable management of the biosludge, there is a progressive trend in the production of biogas as an energy source. Generally, the biogas is practically produced from the anaerobic treatment of sludge on a large scale. Although there is no sewage treatment plant in the production of biogas from the sludge treatment in Taiwan, a few of municipal wastewater treatment plants are being planned to construct the anaerobic digestion system for the purpose of biogas-to-bioenergy in the near future.

2.3. Industrial wastewater treatment plant

Industrial wastewaters generated from food processing, paper and pulp manufacturing, fermentation (wine-manufacturing) and chemical manufacturing processes generally contain high content of carbon fractions, resulting in high values of chemical oxygen demand (COD) and color in the raw wastewater. In Taiwan, the upflow anaerobic sludge

bed reactor (UASB), which consists of distributor, sludge bed, sludge blanket, and gas/liquid/solid separator, has successfully applied to industrial wastewater treatment plants (WWTP) [9]. In the past, the biogas thus produced from the sludge blanket zone was directly discharged to the atmosphere without any treatment and energy utilization. Recently, there are three (two food processing and one chemical manufacturing) plants (Fig. 1) that have installed biogas-to-electricity facility in the wastewater treatment system based on the considerations of environmental sustainability and energy conservation. It is also noted that a few of petrochemical manufacturing (e.g. purified terephthalic acid) and food processing (e.g. fructose) plants in Taiwan utilized the biogas that produced from the anaerobic wastewater treatment process for useful purposes such as process steam.

2.4. Swine waste and wastewater treatment plant

According to the previous paper [10], the piggery wastes (incl. feces and urine) from hog farmers were partly treated by the three-step wastewater treatment system in Taiwan, which includes solid–liquid separation by screening method, anaerobic fermentation (biogas thus generated), and activated sludge process. The purified biogas contains 99% methane, which can be safely stored in a red mud plastic (RMP) bag or compressed cylinder after dehydration and condensation. Currently, the biogas has been used as useful fuels for the stove heating, piglet warming, water pump, and electricity generation. As listed in Table 2, the total amounts of biogas energy utilization from the piggery waste and wastewater system are estimated to be about 790 kW by the installation capacity.

3. Overview of MSW generation and management

According to the Article 2 of Waste Disposal Act (WDA) newly amended in October 2001, the wastes are classified into general wastes and industrial wastes in Taiwan. 'General wastes' are defined as follows: these wastes include garbage, excrement and urine, animal corpses in solid or liquid form generated by households or other nonindustries, which have capacity to pollute the environment. Obviously, the general waste is almost identical to MSW, which is normally assumed to include all non-industrial community wastes such as residential wastes, commercial wastes and municipal service wastes (excluding treatment facilities) [2].

According to the data examined by Taiwan EPA and shown in Table 3 [11], 58.5% (approx. 4304 thousand metric tons) of MSW by incineration, 24.7% (approx. 1814 thousand metric tons) of MSW by landfill, and 16.7% (approx. 1217 thousand metric tons) of MSW by recycling in 2003. In contrast to the data during the 1990s also listed in Table 3, the percentages of MSW treated by incineration, landfill and recycling are 3–24, 71–92 and 0–2%, respectively. For example approximately 3 and 92% of MSW were treated by incineration and landfill, respectively, in 1993. To resolve effectively MSW management, Taiwan EPA has adopted a strategy favoring incineration as the primary treatment and sanitary landfill as a supplement because the composition of MSW mostly contains the combustibles such as paper, kitchen garbage and plastics. In summary, the following combustible materials in MSW (dry basis) were found as follows: paper 25–36%, textiles 4–6%, garden/trimmings 3–6%, food wastes 18–28%, plastics 18–22%, and leather/rubber 1–2%, as shown in Table 4.

Table 3
MSW generation and management in Taiwan

Year	Generation[a] (10^3 metric ton)	Management			
		Incineration (%)	Landfill (%)	Recycling (%)	Others (%)
1992	8001	3.19	90.44	0.10	6.27
1993	8217	3.03	91.76	0.00	5.21
1994	8493	4.86	89.88	0.02	5.24
1995	8708	14.94	79.24	0.07	5.75
1996	8736	15.62	79.15	0.03	5.20
1997	8801	19.05	75.06	0.16	5.73
1998	8992	19.36	74.36	1.25	5.03
1999	8716	23.18	71.42	1.94	3.46
2000	8353	38.66	54.10	5.75	1.49
2001	7839	47.67	43.76	7.45	1.12
2002	7602	56.78	30.79	11.60	0.83
2003	7355	58.52	24.66	16.53	0.29

Source: [11].
[a]Including recyclables (kitchen garbage, recyclable containers and articles) and non-recyclables (disposed of to landfills).

Table 4
Physical compositions of municipal solid waste in Taiwan

Year	Combustibles								Incombustibles[a]
	Papers	Fibers/ clothes	Woods/ leaves	Kitchen garbage	Plastics	Rubbers/ leathers	Others	Sum	Sum
1992	24.86	3.97	5.06	25.73	19.14	1.73	2.45	82.94	17.06
1993	27.84	5.13	5.79	23.47	18.01	1.55	1.15	82.94	17.06
1994	29.98	4.81	4.69	23.50	18.90	0.80	4.31	86.99	13.01
1995	32.17	6.21	5.82	17.94	18.27	0.88	3.34	84.62	15.38
1996	30.95	5.05	5.89	18.97	17.83	1.08	4.72	84.48	15.52
1997	29.13	5.80	4.86	24.90	19.57	1.13	2.11	87.50	12.50
1998	32.77	5.27	4.81	18.29	20.14	0.83	4.54	86.58	13.42
1999	35.83	5.20	4.89	21.83	19.85	0.60	1.97	90.17	9.83
2000	26.37	6.06	3.36	27.76	22.00	1.35	0.44	87.34	12.66
2001	26.55	4.81	4.06	27.32	21.10	0.48	5.06	89.38	10.62
2002	30.01	3.65	4.43	23.34	20.23	0.60	8.17	90.43	9.57
2003	32.97	3.78	3.88	27.19	21.36	0.22	3.58	92.98	7.02

Source [11]; unit: % dry wt.
[a]Including metal, glass, ceramic, stone, sand (>5 mm) and other inerts.

4. Estimation of methane generation from landfills

The anthropogenic methane sources from LFG are almost produced by the anaerobic decomposition of various organic matters (i.e. kitchen garbage, paper and pulp, wood, and leaf). Because of the simplicity and reliability in requiring less data and expertise than other

theoretical methods such as heating value, carbon content, chemical composition, and physical composition methods [12], a simple and straightforward method (i.e. IPCC method) was used to estimate CH_4 generation from the source in the present work [13]. According to the IPCC methodology, this method is on the basis of the quantities of MSW disposed of to landfills and other generation factors including fraction of degradable organic carbon (DOC) in MSW, fraction of dissimilated DOC, and methane fraction (ratio) in biogas. In a word, estimating CH_4 generation from the MSW landfills by the IPCC method was calculated as follows:

$$CH_4 \text{ emissions (Gg/yr)} = MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12$$

where MSW_T is the total MSW generated (Gg/yr), MSW_F the fraction of MSW disposed of to landfills, MCF the methane correction factor, DOC the fraction of degradable organic carbon, DOC_F the fraction of total DOC that actually degrades, F the fraction of methane in LFG (default is 0.5).

Table 3 lists the data of MSW_T and MSW_F in Taiwan during 1992–2003 [11]. The default values (0.4–1.0) for MCF are dependent on the types of MSW landfill practices. In the paper, the MCF default value of 0.6 was set because most of MSW landfill practices in Taiwan were unmanaged, and a few of MSW landfill practices were managed and openly dumped [14]. With respect to the DOC, there is a considerable variation on the default value ranging from 0.08 to 0.21 [13]. According to the IPCC methodology and the data in Table 4 [11], the estimation of DOC was modified as follows:

$$DOC = 0.4 \times P + 0.15 \times K + 0.3 \times W$$

where P is the fraction of papers in MSW, K the fraction of kitchen garbage in MSW, W the fraction of woods/leaves in MSW.

It is noted here that the data thus estimated are about 0.17, which is acceptable as compared to the carbon data in Table 5 [11]. Further, the DOC_F should be considered because the biodegradation of DOC does not occurred totally over a long period of time.

Table 5
Chemical analyses of municipal solid waste in Taiwan

Year	Moisture (%)	Ash (%)	Combustibles (%)							
			Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Organic	Others	Sum
1992	51.97	16.15	16.50	2.81	11.44	0.79	0.18	0.16	0.00	31.88
1993	50.06	16.02	17.04	2.82	11.99	0.52	0.19	0.30	0.07	32.92
1994	53.21	12.43	19.08	2.38	12.00	0.50	0.12	0.18	0.10	34.36
1995	48.14	14.40	18.60	2.90	14.45	0.51	0.14	0.18	0.68	37.47
1996	50.60	13.79	18.99	2.82	13.06	0.45	0.12	0.16	0.00	35.61
1997	46.03	13.12	20.44	3.50	15.62	0.70	0.19	0.39	0.00	40.85
1998	51.06	12.60	18.47	2.65	14.23	0.74	0.06	0.18	0.00	36.34
1999	50.76	10.08	18.87	2.85	15.95	1.19	0.09	0.21	0.00	39.17
2000	45.02	14.07	21.12	4.01	14.81	0.59	0.14	0.23	0.00	40.91
2001	55.80	11.34	18.24	2.62	9.11	2.56	0.10	0.12	0.11	32.86
2002	51.24	11.01	20.45	3.04	13.04	0.57	0.10	0.25	0.30	37.75
2003	55.69	7.51	18.71	2.84	13.92	0.49	0.20	0.16	0.48	36.80

Source: [11].

Table 6
Estimation of methane generation from MSW landfill treatment in Taiwan

Year	MSW disposed[a] (10^3 metric ton)	MCF	DOC	DOC_F	*F*	Annual methane generation (10^3 metric ton)
1992	7236	0.60	0.153	0.77	0.50	341
1993	7540	0.60	0.164	0.77	0.50	381
1994	7634	0.60	0.169	0.77	0.50	397
1995	6900	0.60	0.173	0.77	0.50	368
1996	6915	0.60	0.170	0.77	0.50	362
1997	6606	0.60	0.168	0.77	0.50	342
1998	6686	0.60	0.173	0.77	0.50	356
1999	6225	0.60	0.188	0.77	0.50	360
2000	4519	0.60	0.157	0.77	0.50	219
2001	3430	0.60	0.159	0.77	0.50	168
2002	2341	0.60	0.168	0.77	0.50	121
2003	1814	0.60	0.184	0.77	0.50	103

[a]Obtained by the data in Table 3.

In the paper, the default value of 0.77 was adopted on the estimation of methane emissions from MSW landfills according to the recommendation of the IPCC methodology [13].

The CH_4 generation from the land disposal of MSW in Taiwan during 1992–2003 was estimated and listed in Table 6. Based on these results, several observations can be made as follows:

- Annual CH_4 generation was close to about 360 Gg (thousand metric ton) during 1992–1999. In 1994, landfill CH_4 emissions reached to maximum amount of approximately 400 Gg mainly due to increased amount in MSW deposited in landfills.
- From 2000 to 2003, annual CH_4 generation from landfills decreased by about 30%. In 2003, the amount was only 103 Gg. This significantly downward trend in total CH_4 generation from landfills was attributable to the result of large increases in the amount of MSW recycled and incinerated at the same period [2].
- Since 2000, the amount of LFG-to-electricity began to increase in Taiwan, which was expected to reduce the net CH_4 emissions from MSW landfills. With respect to the CH_4 mitigation, it will be further discussed below.

5. Governmental strategy for promoting LFG utilization

Renewable energy is a sustainable and clean energy derived from natural sources. In order to encourage the use of the clean energy in Taiwan, the current promotion regulations related to renewable energy utilization are mainly based on the *Statute for Upgrading Industries* (SUI), which was originally promulgated and became effective in Dec. 1990 and was thereafter revised in Jan. 1995, Jan. 2002 and Feb. 2003, respectively [10]. Under the authorization of Article 6 of SUI, the regulation, known as 'Regulation of Tax Deduction for Investment in the Procurement of Equipments and/or Technologies by Energy conservation, or emerging/Clean Energy Organizations', has first been promulgated by Ministry of Finance (MOF) in July 1997, and thereafter revised in Nov. 1999, Jul. 2000, Sep. 2001 and Jan. 2003, respectively. These specified organizations shall be granted

credits on the profit-seeking enterprise income tax for the current year if they themselves use these equipments and/or technologies according to the following percentages of total purchase cost ($>$NT$ 600,000, or about US$ 19,500) in the current year:

- 13% for emerging/clean energy utilization equipments.
- 10% for emerging/clean energy utilization technologies.

On the other hand, LFG for electricity generation has been promoted under funding of the air pollution control fee (mainly original from an excise tax on gasoline) of *Air Pollution Control Act* (APCA) prior to the legislation of the Statute for Renewable Energy Development (Draft). Under the authorization of APCA, the regulation, known as 'Promotion Guideline to Encourage the Use of Landfill Biogas for Electricity Generation', has first been promulgated by Taiwan EPA in June 1999, and thereafter revised in Dec. 2000 and Jan. 2003, respectively [15]. In the Regulation, firms that generate electricity by using CH_4 gas from landfills can receive a subsidy at a fixed rate of NT$ 0.5/kW-h ($\fallingdotseq$US$ 0.016/kW-h) based on the actual amount of electricity purchased by the power company.

6. Status of electricity generation from LFG

The biogas production from sanitary landfill represents one of potential green energy or renewable energy from the viewpoint of sustainable development because its composition mainly includes GHGs (i.e. CH_4 and CO_2). Until the mid-1990s, in order to mitigate GHGs emissions from LFG based on UNFCCC, the Taiwan government was active in coordinating private sector to construct LFG-to-electricity facility since 1999 under the policy encouragements of the EPA and Council for Economic Planning and Development (CEPD). Currently, there are four LFG-to-electricity facilities, which are located in Nankang (Taipei city), Mucha (Taipei city), Wenshan (Taichung city) and Nantzu (Kaohsiung city), respectively, as shown in Fig. 1 and summarized in Table 7. The total installation capacity of LFG-to-electricity sums up to 24.52 MW.

From the process diagram (Fig. 2) of the LFG-to-electricity facility [16], the system includes extraction well, biogas collection station, concentration/separation tank, blower unit, filtration purification unit, engine-generator unit, and power output. The biogas in the various units was transferred through the plastic (high density polyethylene, HDPE) pipe without the possibility of leakage in operation. Basically, the LFG-to-electricity consists of collection/removal system and generation/output system, which are briefly described as follows.

6.1. Collection and removal system

In order to capture rapidly and effectively biogas in the sanitary landfill, the active collection type was designed by using blower equipment. The check valve was installed at suction inlet and output of blower to prevent the recycle from the pipeline while extracting. Under the induced extraction, the well will become a low-pressure vacuum zone, resulting in the biogas inflow through the vertically percolated pipe. Each extraction well was also regulated by control valve to take a considerable amount of biogas flow rate. Regarding the prevention of corrosion associated with the interaction between H_2S and moisture, the moisture was first condensed and further separated from the biogas by compression and

Table 7
Sanitary landfill sites in operation for electricity generation in Taiwan

Item	Northern region		Central region	Southern region
	Nankang (Taipei city)	Mucha (Taipei city)	Wenshan (Taichung city)	Nantzu (Kaohsiung city)
Disposal period	1993 ~ (in operation)	1985 ~ 1994	1995 ~ (in operation)	1985 ~ 1999
Total MSW disposed of (10^3 metric ton)	~ 2500	~ 3200	~ 2500	~ 9000
Start date on LFG for electricity	Nov. 1999	Apr. 2002	Sep. 2000	Apr. 2000
Current installation capacity (MW)	6.81	5.45	5.45	6.81
Maximum installation capacity (MW)	6.81	10.90	6.81	8.17
Service years (yr)	10–20	10–20	10–20	10–20
Biogas treatment rate[a] ($10^3 m^3$/yr)	25,500	25,500	25,500	25,500
Average methane concentration (vol%)	50	50	50	50
Methane reduction rate (metric ton/yr)	~ 8340	~ 8340	~ 8340	~ 8340
Net GHG reduction rate[b] (10^3metric ton/yr)	~ 169	~ 169	~ 169	~ 169

[a]Predicted value.
[b]Net GHG reduction rate (as CO_2 equivalent) ≒ methane reduction rate × [23–(44/16)].

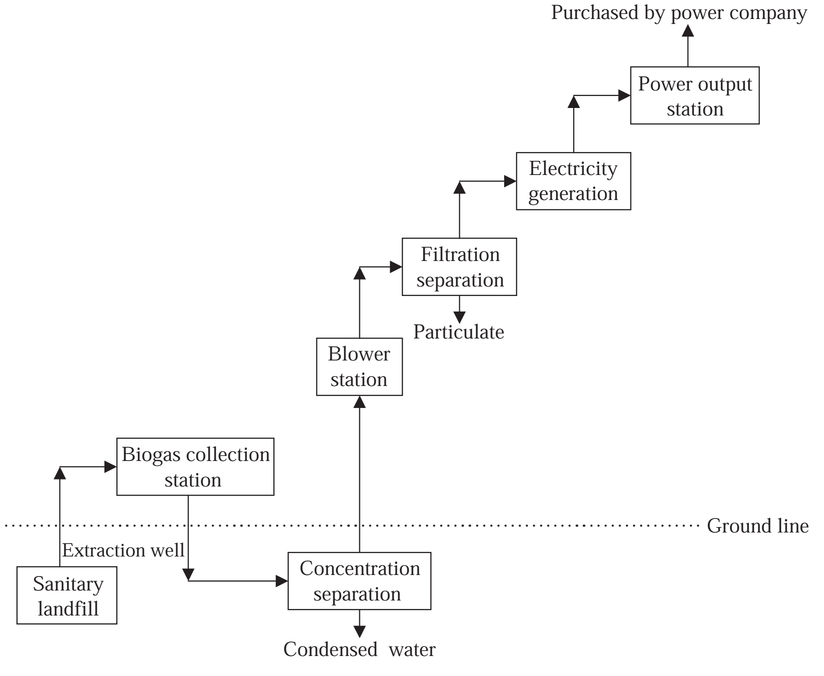

Fig. 2. Flow diagram of biogas extraction and power generation process in the MSW landfill.

cooling. Condensate drains were located at all low spots and proper intervals along biogas collection pipelines. The condensed water was percolated back into the landfill. In order to further purify the dehumidified biogas, the filtration device was equipped to remove particulate ($>0.4\,\mu m$) from the dehumidified stream.

6.2. Electricity generation and output system

Using internal combustion (IC) engines, the purified biogas was used to generate electricity. The capacity of each power generation module was set at 1.0–1.4 MW which was generated by the engine generator. In order to control the noise from IC engines, each module was also installed at the soundproof box, which contained an independent electricity operation system. A programmable logic controller unit controlled total generation system including startup, shutdown, loading control and alarm. The voltage of electricity was further transformed to 11.4 kV or proper voltage, which was linked with the distribution system of the local power company. Finally, the green energy was transferred to the end user.

7. Benefits of GHGs emissions reduction from LFG-to-electricity

In the past, LFG was viewed as an odorous nuisance, one of major GHGs emission sources, and even became a safety hazard in Taiwan. Today, the LFG-to-electricity facilities provide a unique green energy. Based on the data (i.e. 24.5 MW of total installation capacity) in Table 7, the socio-economic and environmental benefits of electricity generation from LFG are qualitatively and quantitatively described as follows.

7.1. Quantitative benefits

- CH_4 reduction: 33,360 metric tons/yr (based on $1.0 \times 10^8\,m^3/yr$ and 50 vol% methane).
- Electricity generation: $1.6 \times 10^8\,kW - h/yr$ (based on 5500 kcal/m^3 heating value, 25% energy efficiency).
- Equivalent electricity charge saving: US\$ 1.1×10^7/yr (based on US\$ 0.08/kW-h).
- Equivalent CO_2 mitigation: 6.8×10^5 metric ton/yr (based on its global warming potential (= 23) with 100-year time horizon relative to GWP of CO_2) [13].

7.2. Qualitative benefits

- To coordinate with energy policy: promotion of diversification of primary energy, and fulfillment of energy-related technology development.
- To upgrade environmental and living quality: reduction of odor problem, mitigation of VOCs hazards, and prevention of landfill fires.
- To enhance land utilization: acceleration of landfill remediation, and increase of public activity space.
- To upgrade social education and national impression: promotion of energy and environmental education for public, and improvement of environmental protection stress from UNFCCC.

8. Conclusions and recommendations

In the past decade, energy supply/consumption related to global warming has been the focus of environmental legislation and economic development for pursuing sustainable

development and creating green energy in Taiwan. It is obvious that LFG-to-electricity has been relatively attractive under the policy encouragement and economic feasibility. During this period, CH_4 emissions from MSW landfills in Taiwan were estimated to be at about 360 thousand metric tons annually in the 1990s, and then expected to decrease significantly over the next several years (2000–2003) due to the new MSW management policy. To greatly promote the bioenergy utilization from MSW landfills in Taiwan, the following measures are recommended and enhanced:

- Require high energy consumption industries (e.g. paper and pulp, food processing and petrochemical manufacturing) to make net energy reduction by utilizing biogas from the wastewater treatment plants.
- Research a commercial bio-technology process for hydrogen generation from high-organic bioresources because hydrogen energy has been recognized as the most clean fuel, without GHGs emissions.
- Develop an available technology for capturing H_2S from LFG to prevent the formation of SO_2 from the biogas combustion for generating electricity and other energy uses.
- Demonstrate commercial feasibility on utilizing bioenergy from MSW composting, which has been listed as a new policy for MSW management in the next decade in Taiwan.
- Exploit LFG-to-electricity at other managed MSW landfills.

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